Ion Acceleration from ultrafast laser driven liquid microdroplets

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Laser Plasma Targetry Workshop

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IBS Center for Relativistic Laser Science

GIST Ultrashort Quantum Beam Facility

- PW Ti:Sapphire Laser
  - Beam line I: 30 fs, 1.0 PW @ 0.1 Hz
  - Beam line II: 20 fs, 4 PW @ 0.1 Hz
- 100-TW Laser: 30 fs, E = 3 J @ 10 Hz

recent developments to increase proton energy

Two principal ways of increasing the maximum proton energy are

- optimization of the target design:
  - atomic composition,
  - density,
  - structure,
  - thickness, (ultrathin targets)
  - Using complex target shapes
  - transverse size.
- the laser pulse characteristics:
  - pulse duration
  - power,
  - intensity,
  - focal spot size,
  - polarization,
  - pulse shape, etc.

Open problems

- Besides the intense-laser interaction with foil targets with thicknesses of μm – nm, no other target concept could be demonstrated so far to be capable of proton emission with energies in excess of several tens of MeV.

- An optimized laser target concept in terms of laser energy consumption cannot be given.

- For any application one needs high repetition rate, reproducible, debris free target system

In a quest of principal ways of increasing the maximum proton energy, controlling the beam divergence, and spectrum for applications one needs alternative approaches

motivation – mass limited targets

Specifics of mass-limited targets

- they support the planar acceleration geometry;
- they confine the electrons within the target and prevent their angular spreading ;
- they enable the electrons to access the rear side by passing around the target.

transverse confinement leads to an accumulative effect and can increase the peak value of the accelerating gradient.

we explore ion acceleration dynamics from:

- **isolated single droplet (droplet with 15 μm in diameter)**
- **spray of liquid droplets (droplets ~150 nm in diameter) (patented)**

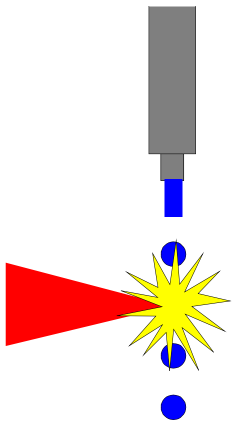
These are: high repetition rate, reproducible, almost debris free target system

Patent 20060054238 “Device and method for the creation of droplet targets”. Inventors: Ter-Avetisyan, S., Schnuerer, M., Nickles, P.-V.

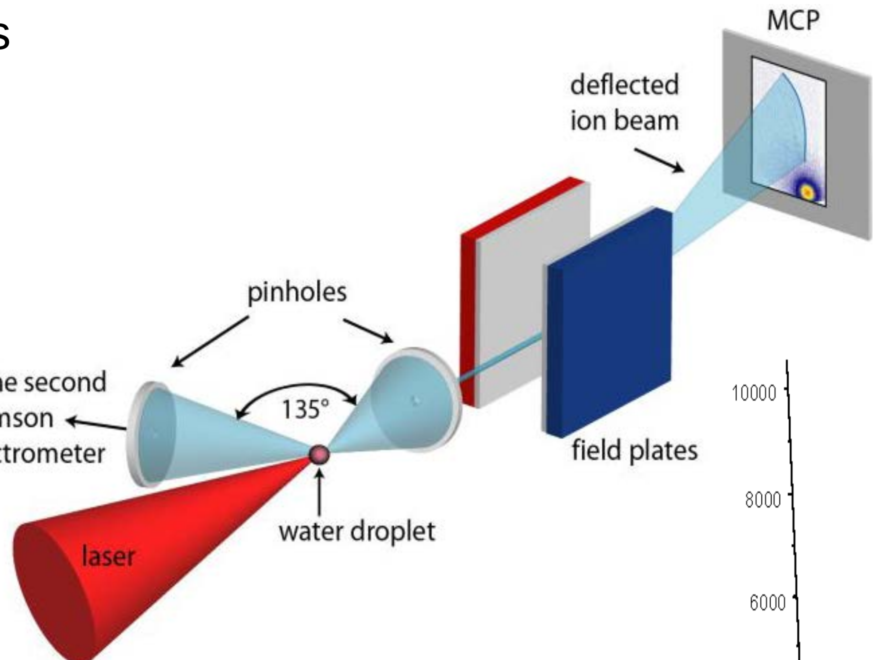
experimental setup and parameters

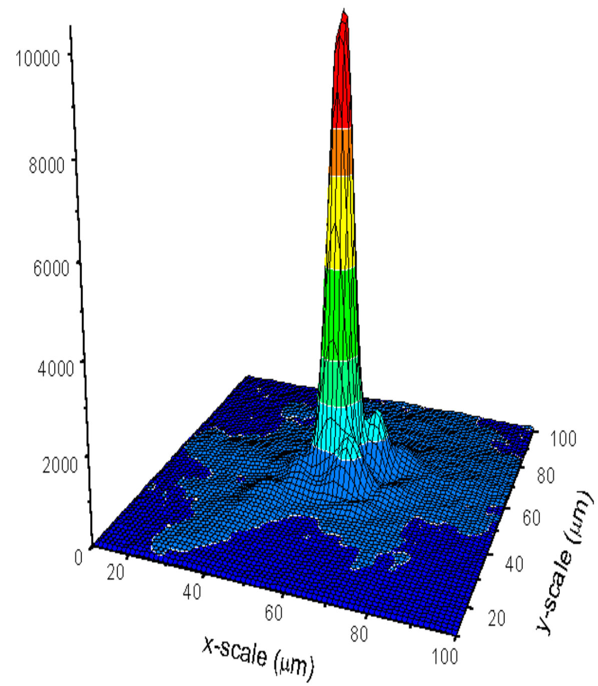
~ (1-5)×10^{19} W/cm^2, ~1 J, 35 fs

H_2O / D_2O- Jet-targets



droplet diameter 15 µm

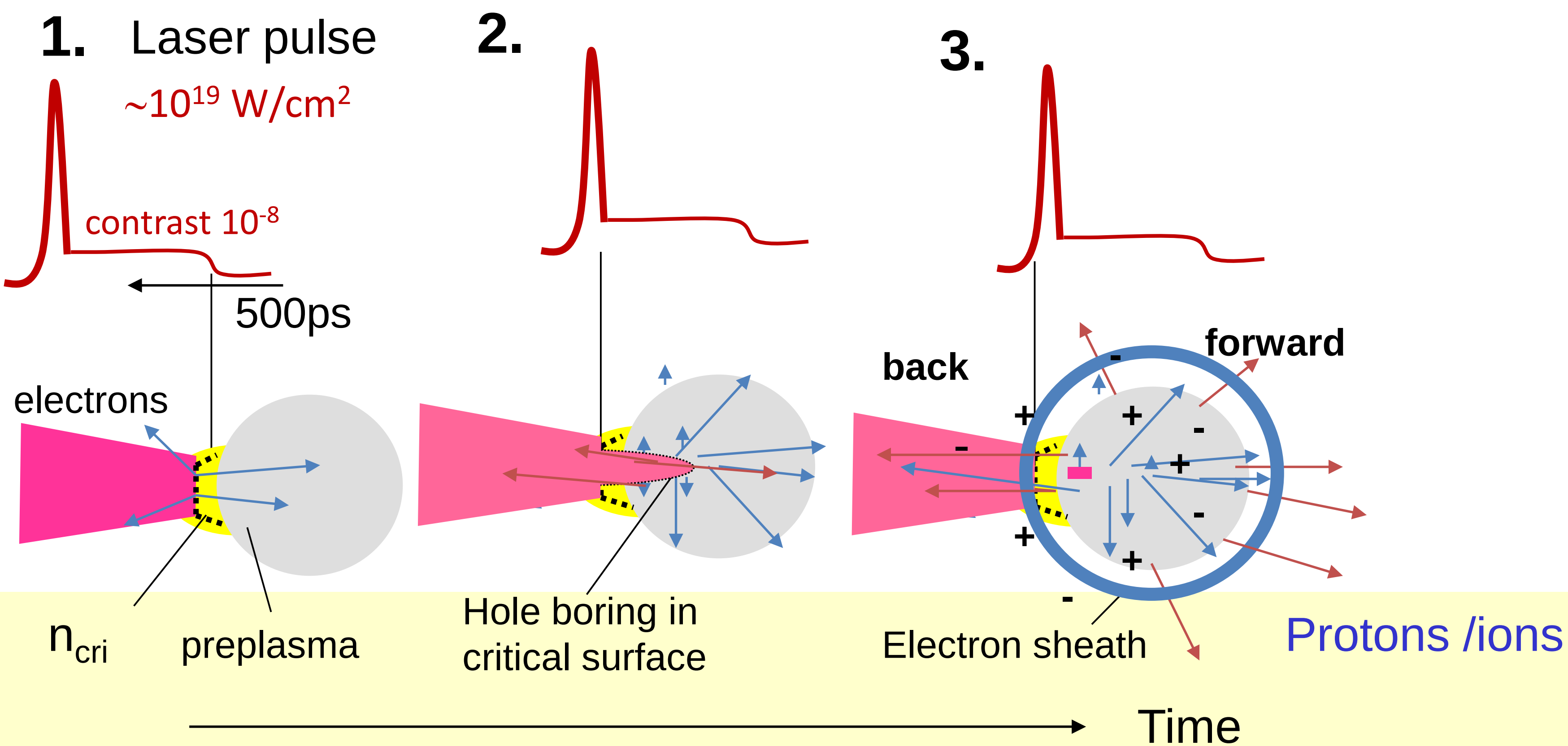




Capillary Nozzle
Micro-Jet Components, Sweden

best: 30 % energy in a 5.5 µm focal area (diffraction limit)

plasma dynamics at fs-laser driven water droplet



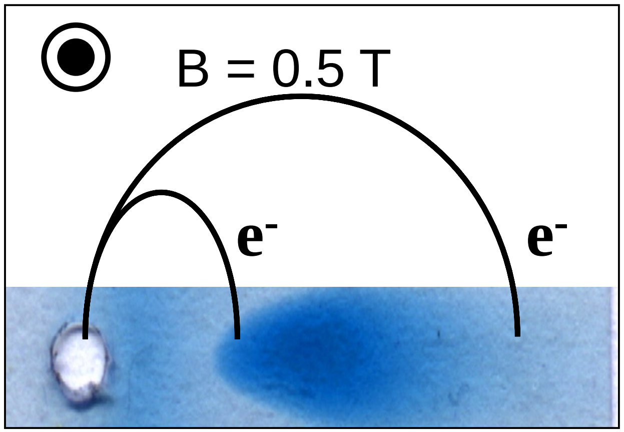
essential for ion acceleration scenario:

- electron dynamic, and
- spatial and spectral ions emission characteristics

e^- spectra reveals a charge up of the droplet

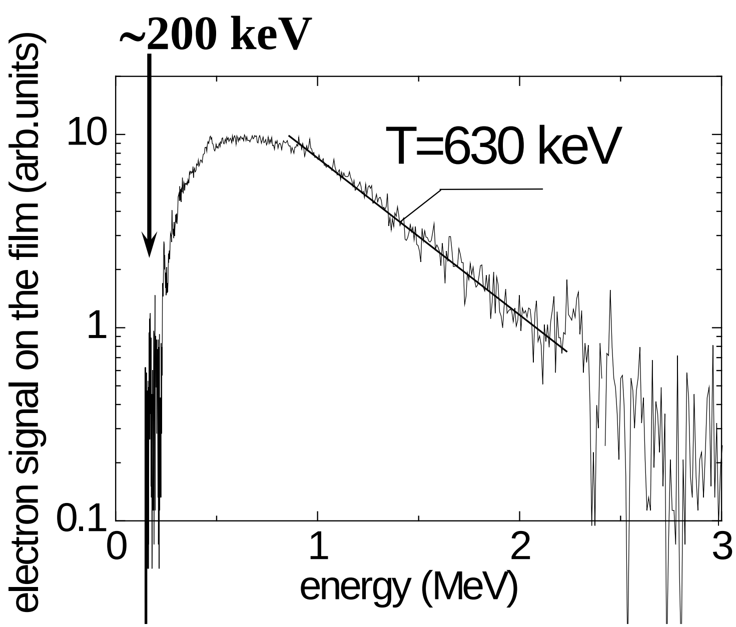
Laser: 35 fs, 0.8J, ~ 10^{19} W/cm^2, contrast ~ 10^{-7}

measured hot electron spectrum with magnet spectrometer



e^- spectrum on GAF-chromic film: HD810

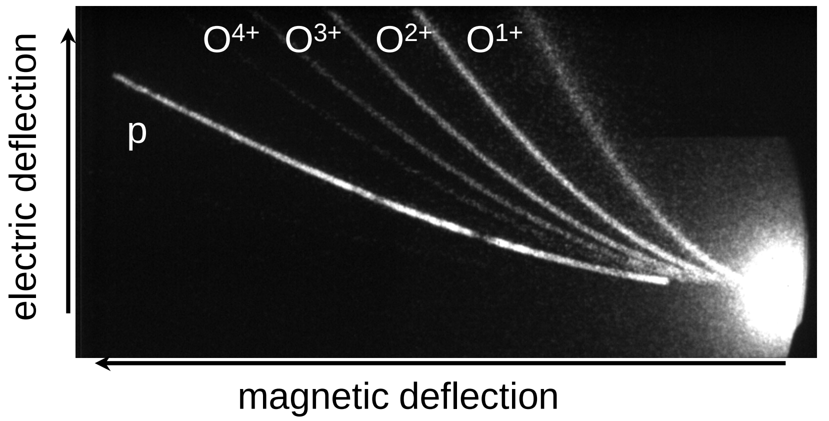
non-energy dependent response of the film for electrons above 10 keV



at ~ 10^{19} W/cm^2
ponderomotive potential ~ 640 keV

The hot electrons are producing an ambipolar potential which will accelerate the ions

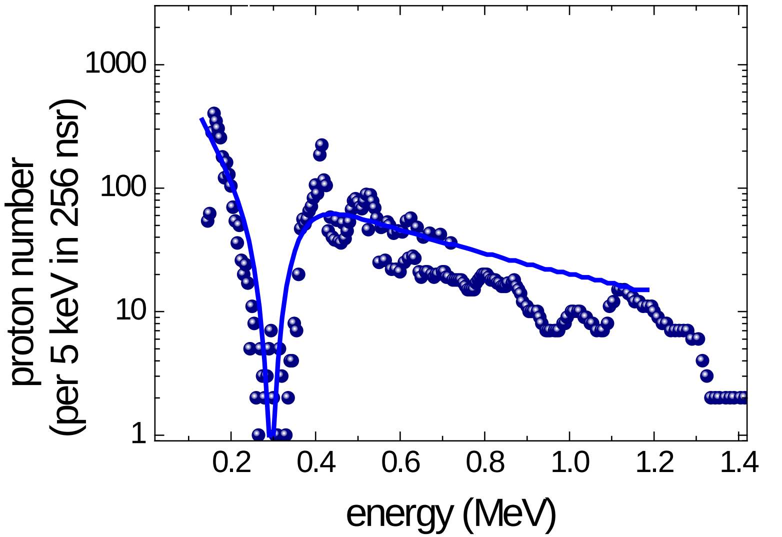
multi electron-temperature plasma

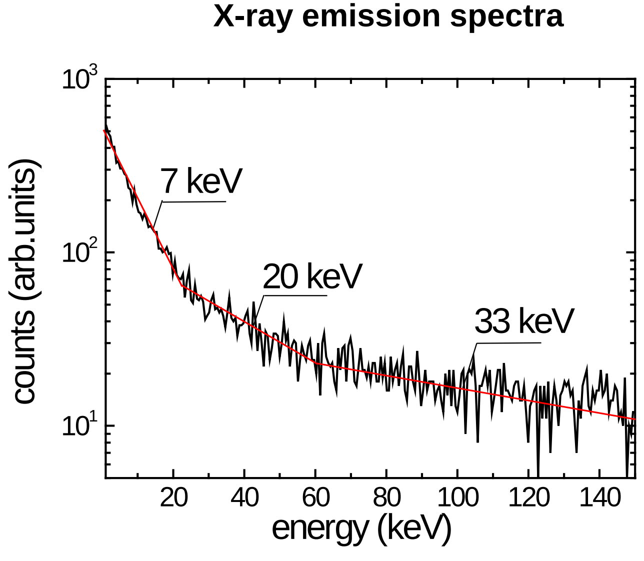


Model of free plasma expansion with

two electron temperatures

Wickens, .Allen and Rumsby PRL 41, 243 (1978)





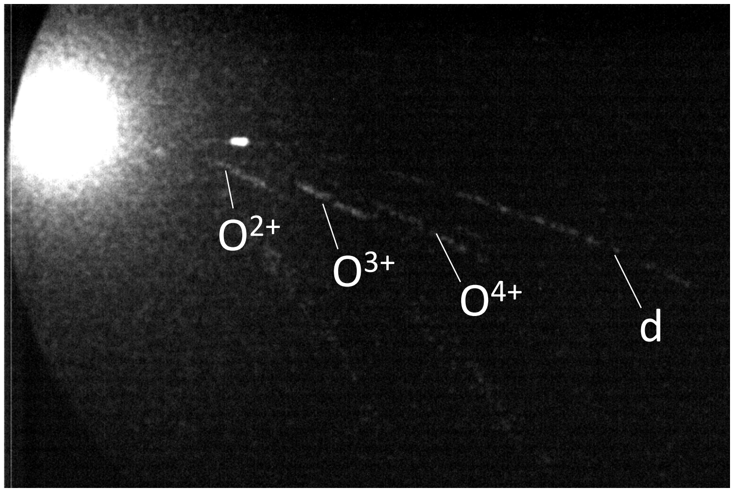
T_{cold} = 7.5 keV and T_{hot} = 74 keV ~ depth

n_{hot} / n_{cold}=1/100 ~ position

S. Ter-Avetisyan e.al., PRL **93** 155006(2004)

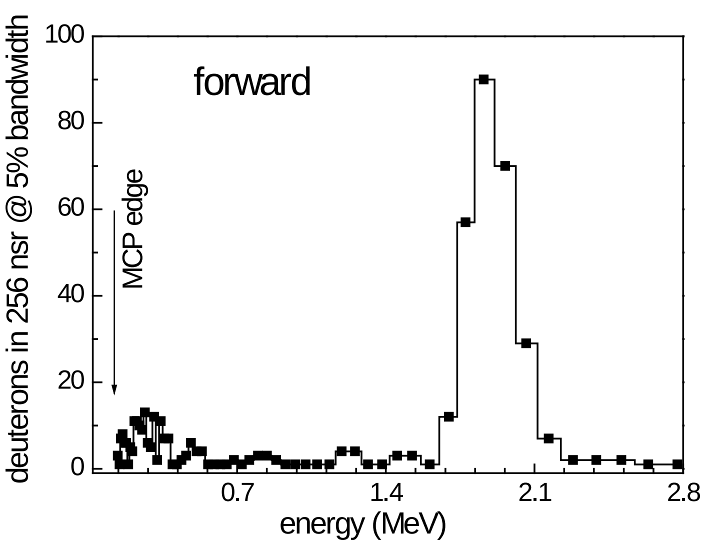
quasi-monoenergetic deuteron bursts

Laser: 35 fs, 0.8J, ~ 10^{19} W/cm^2, contrast < 10^{-8}



→monoenergetic deuteron bunch 2 MeV
in forward direction

15 μm heavy-water droplets



High sheath electric field strength cannot alone account for an nearly monoenergetic energy distribution.

S. Ter-Avetisyan e.al., PRL **96** 145006(2004)

To further elucidate the explosion characteristics of water droplets

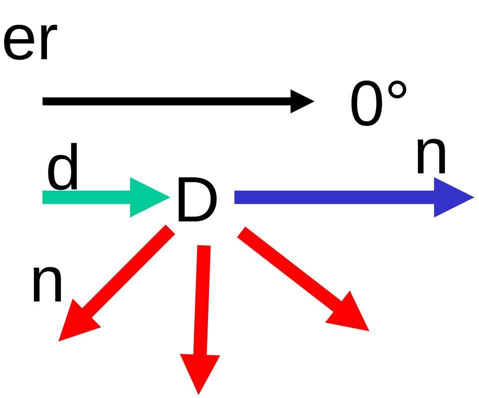
neutron diagnostics was applied

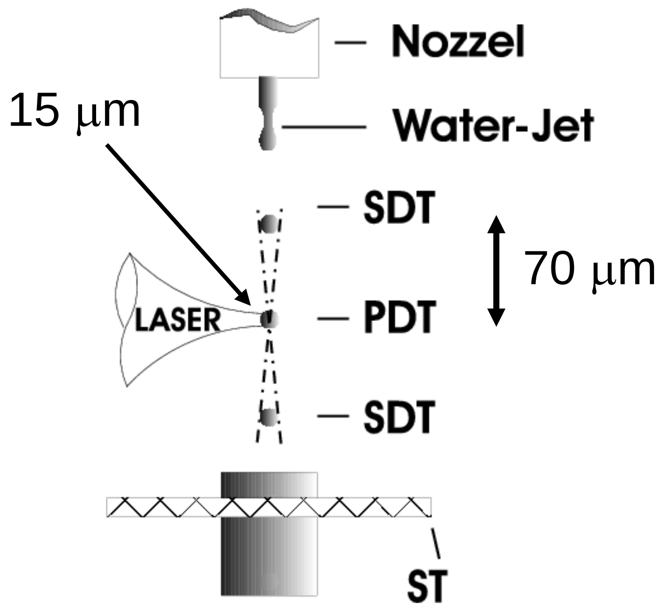
outward and inward

directed ion acceleration from the droplet

- ❑ possible effective neutron source for applications

target system and characteristics





in general we found:

total = (0.7 – 1.4)×10³ n per pulse

- **Calculation:** 40% - 80% of neutros comes from the neighbour droplets:

  cold explosion of the droplet causes mainly emission of **deuterons to the outside**

- **Deuteron acceleration inside a dense droplet target:**

  Energy shift in the neutron spectra shows a **deuteron acceleration along the laser direction**

M. Schnuerer, S. Ter-Avetisyan e.al., PRE 70, 056401 (2004)

model of homogeneous mixture of light and heavy ions

→ spatial separation of the light and heavy ions in the electrostatic field created by the hot electron population

→the oxygen ions do not move during the main pulse, and they create the necessary potential jump.

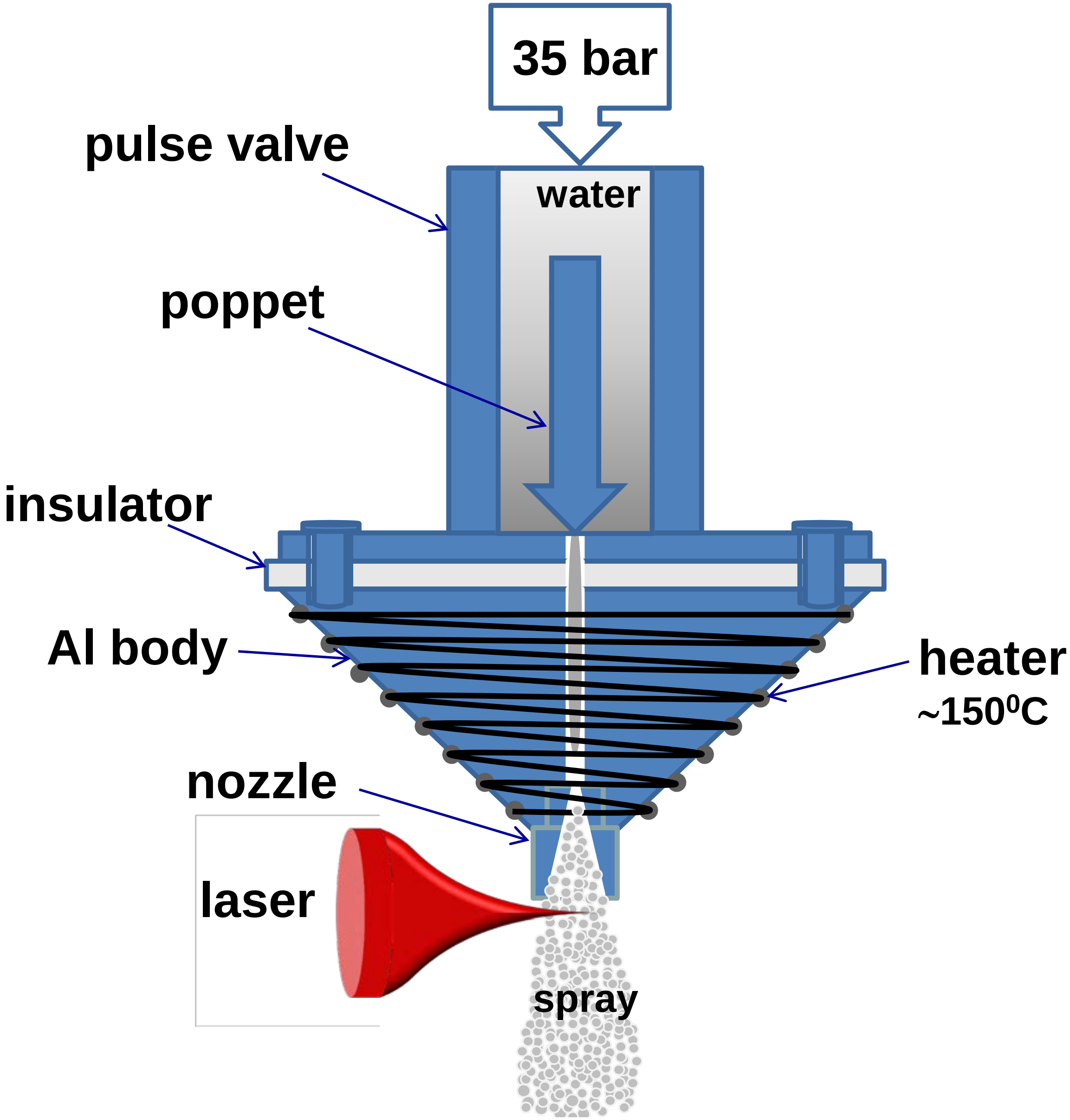
→ all protons crossing the plasma edge will be accelerated in this potential to the same energy and heavy ions create only the low energy cutoff

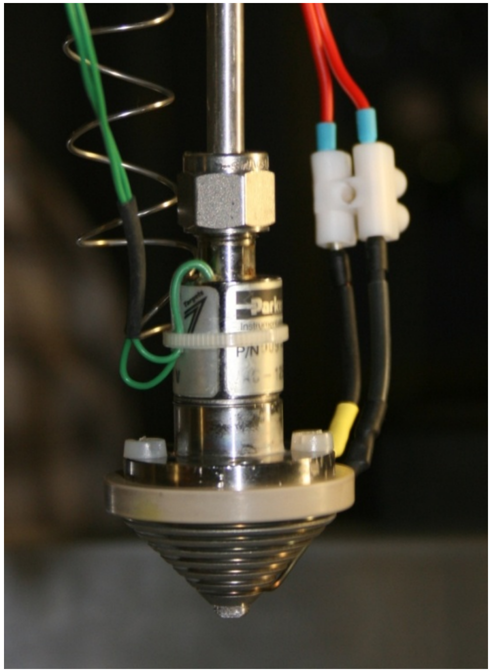
Sub-micron-droplets with a diameter
150 - 180 nm
generated in the spray are
one kind of mass limited targets

S. Ter-Avetisyan, J. Phys. D: Appl. Phys. **36**, 2421 (2003)
R. Prasad, … S. Ter-Avetisyan *Rev. Sci. Instrum.* **83**, 083301 (2012).

Patent; 20060054238 *(2004) Ter-Avetisyan, Schnürer, Nickles,* Device and method for the creation of droplet target

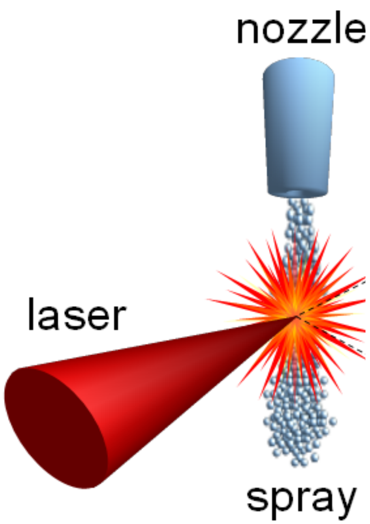
spray generator





Patent; DE 102 60 376 A1 (2004) Ter-Avetisyan, Schnürer, Nickles, Device and method for the creation of droplet target

spray of water droplets



I ~ 5×10^{19} W/cm^2

- single droplet size 150 ± 10 nm
- average spray density 10^{18} cm^{-3}
- droplet density 10^{11} cm^{-3}

$\delta_{\text{skin depth}} < d_{\text{droplet}} < \lambda_{\text{laser}}$

❑ Protons with MeV energies

Schnürer, et al., Appl. Phys. B 78, 895 (2004)

❑ Fusion neutrons from D_2O-spray

reaction probability is found to be two orders of magnitude larger as compared to cluster targets

Ter-Avetisyan, et al., Phys. Plasmas 12, 012702 (2005)

❑ Monoenergetic proton emission

at ~ 3 MeV energy

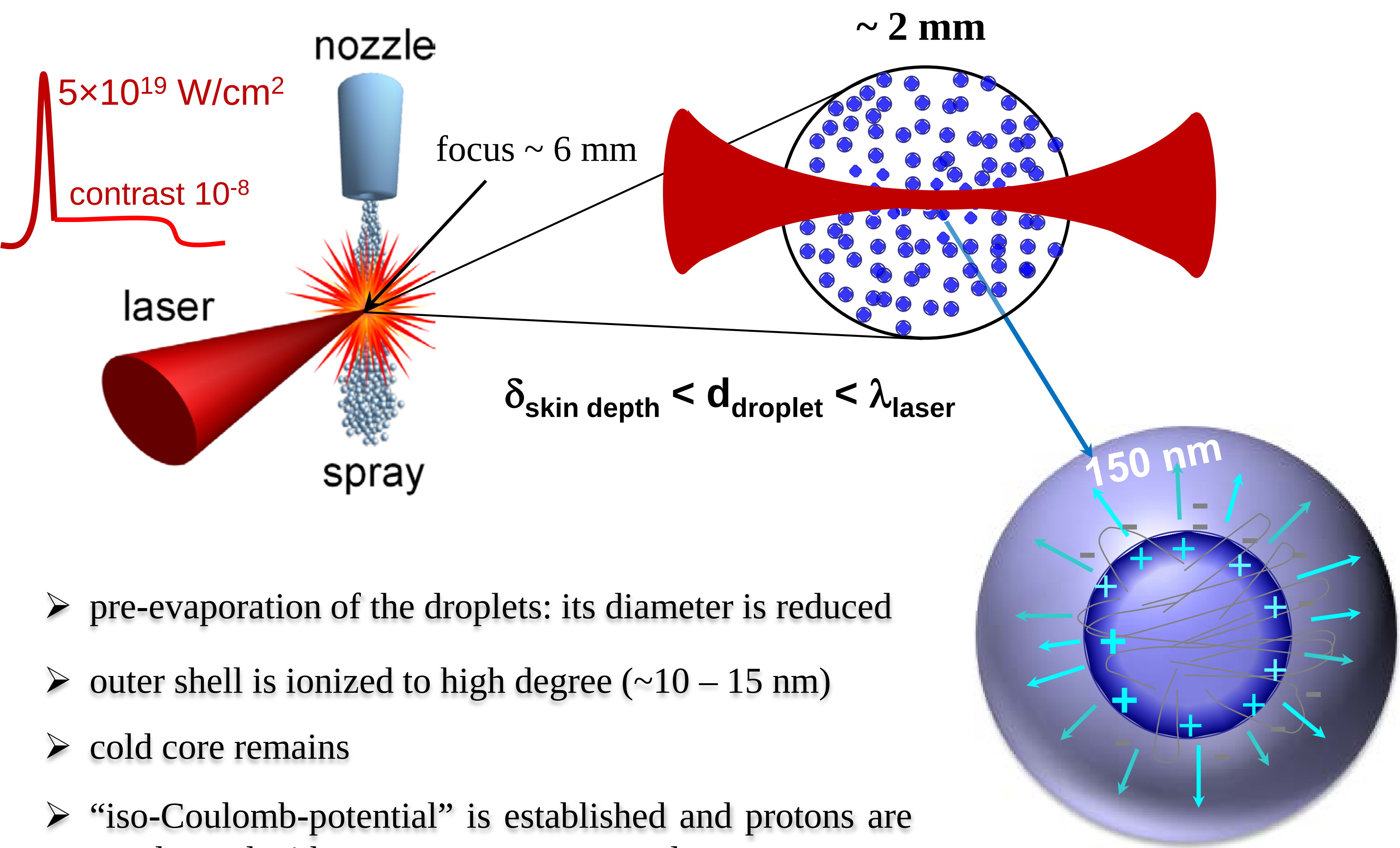
Ramakrishna, et al., Phys.Plasmas 17 083113(2010)
Ter-Avetisyan, et al., Phys.Plasmas 16 043101 (2009)

❑ Copious negative ion emission

10^9 ions/srad

Abicht, et al., … Ter-Avetisyan, APL (2013)
Ter-Avetisyan, et al.,, Appl. Phys. Lett. 99, 051501 (2011).

ion acceleration from the droplets

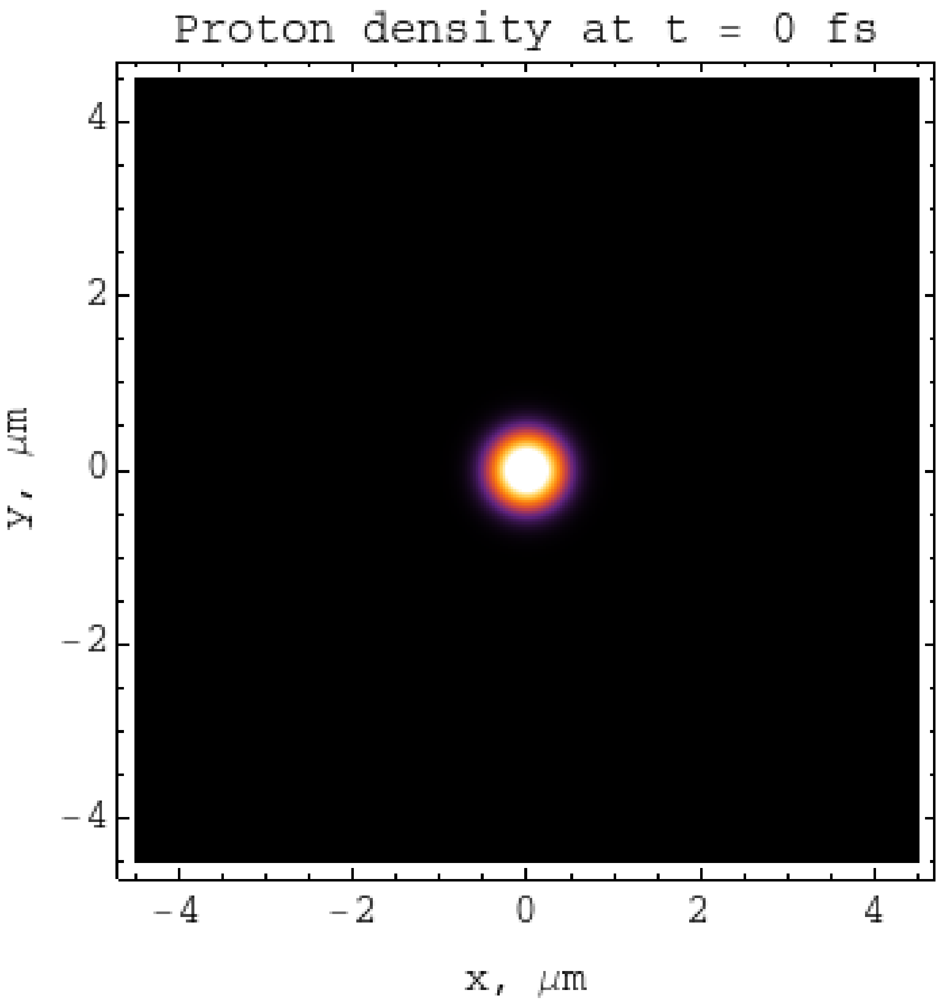


- pre-evaporation of the droplets: its diameter is reduced
- outer shell is ionized to high degree (~10 – 15 nm)
- cold core remains
- "iso-Coulomb-potential" is established and protons are accelerated with a narrow energy spread

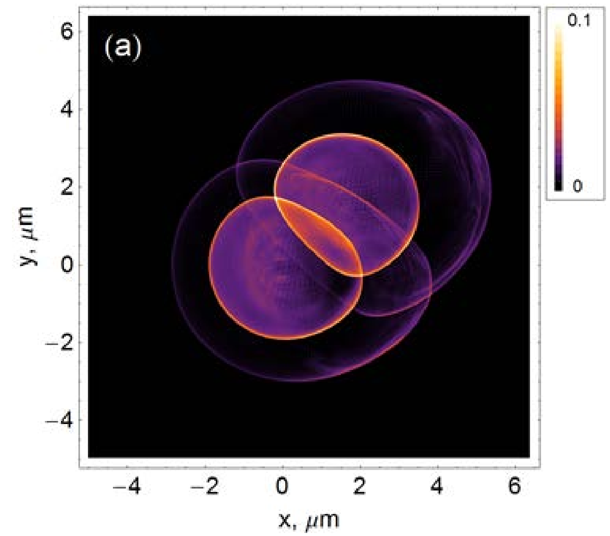
quasi-monoenergetic proton bursts

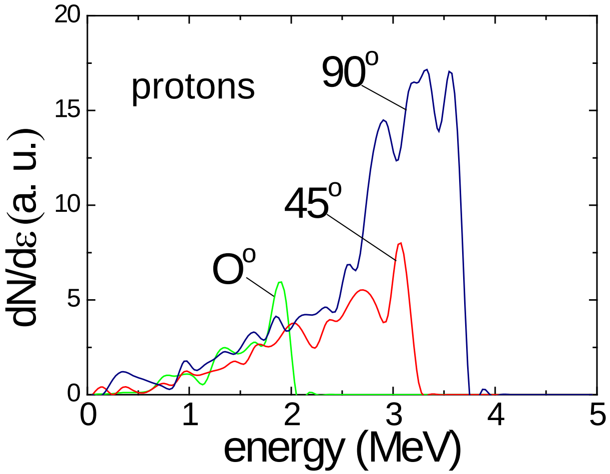
Acceleration scenario strongly depends on modification of the droplets by laser pre-pulse (V. Bychenkov)

5×10^{19} W/cm^2 (1J, 40 fs)



space distribution for exploding droplets



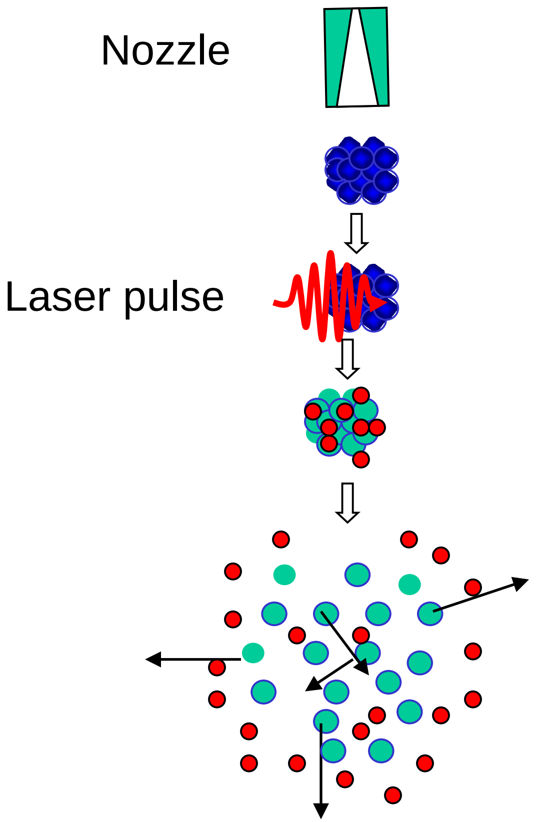


Laser driven neutron yield from heavy water spray target

Quest of effective neutron source for applications

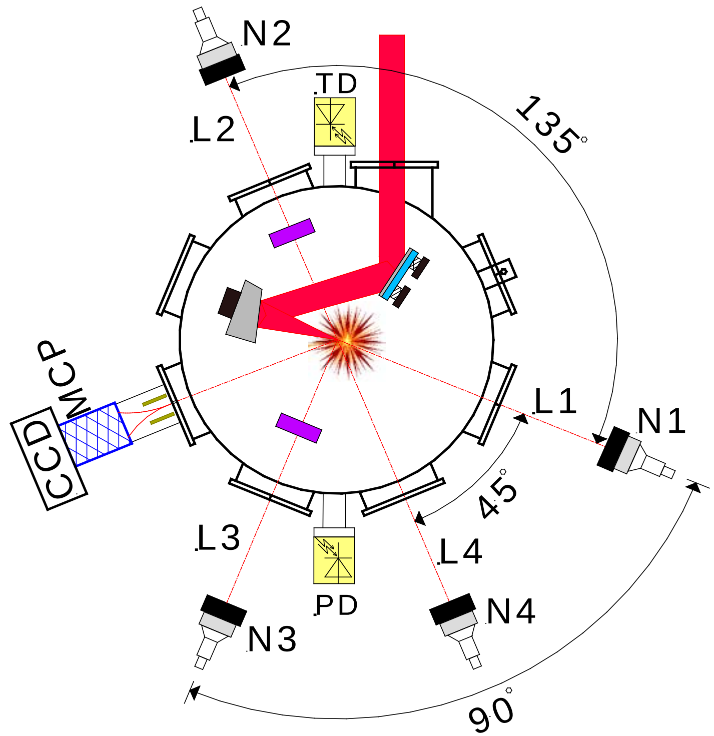
neutron yield from heavy water spray

Interaction geometry:



average density 10^{18} cm^{-3}

Diagnostics



n ~ 6 x 10^3 per pulse
(0.6 J incident at ~ 8 x 10^{18} W/cm^2)

S. Ter-Avetisyan et all. Phys. Plasmas, 12, 012702 (2005)

reaction probability as a ratio:

$$\frac{\textit{number of generated neutrons } (N_n)}{\textit{per accelerated deuteron } (N_D) \textit{ and incident laser energy}}$$

TABLE. Laser driven fusion neutron sources.

Ref.	Target	Neutron (into 4π)	Energy (J)	Laser-pulse parameters Duration	λ (μm)	I_{max} (W/cm²)
[1]	D_2 gas	1×10^6	62	1 ps	1.05	2×10^{19}
[MBI]	D_2O spray	6×10^3	0.6	35 fs	0.8	1×10^{19}
[2]	D_2 clusters	2×10^6	10	100 fs	0.8	2×10^{20}
[3]	CD_4 clusters	1×10^5	2.5	100 fs	0.8	5×10^{19}

[1] S. Fritzler, et al., PRL, 89,165004 (2002),
[2] K.W. Madison, et al.,JOSA B, 20, 113 (2003)
[3] K.W. Madison, et al., Phys. Plasmas, 11, 270 (2004)

To highlight another important property of laser interaction with

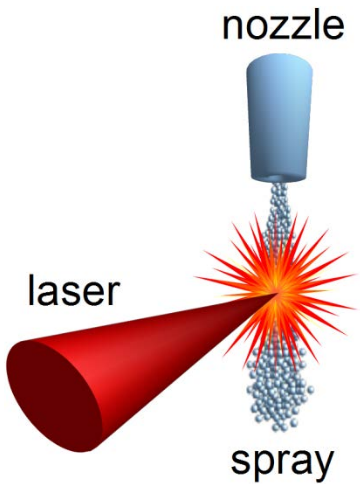
sub-micron-droplet,

namely the capability of acting as a

source of high brightness beams of negative ions and neutral atoms

negative ion acceleration in water spray

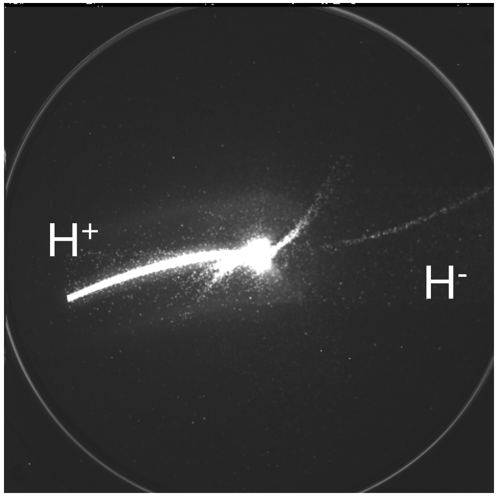
I ~ 5×10^19 W/cm^2, contrast <10^-8 at 10 ps prior the peak



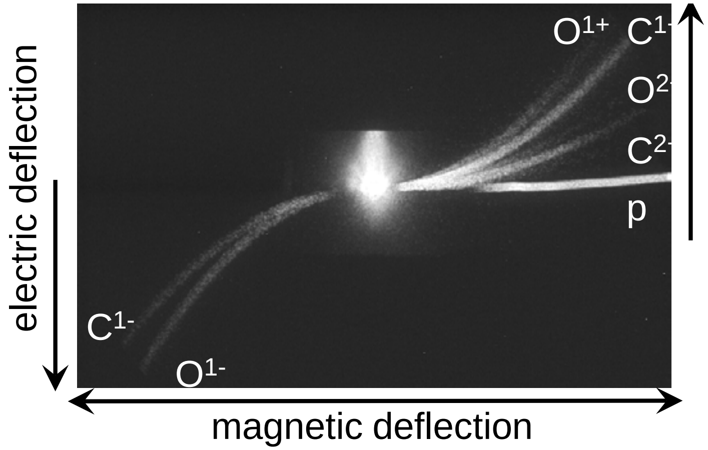
$d_{droplet}$ ~150 -180 nm

density 10^{18} - 10^{19} cm^{-3}

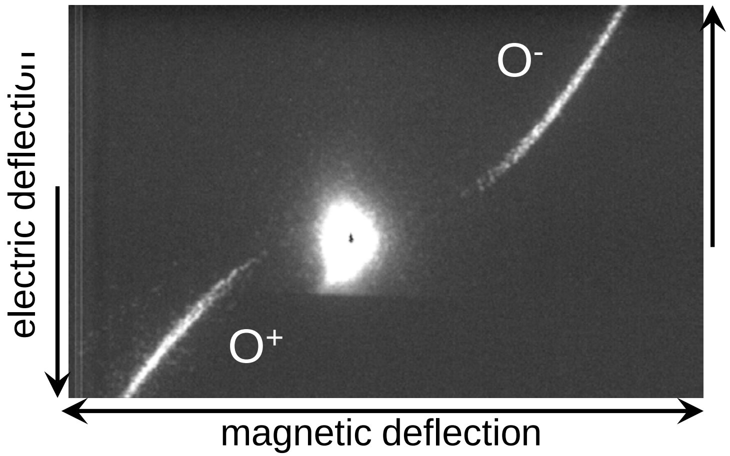
H^- ~ 150 keV



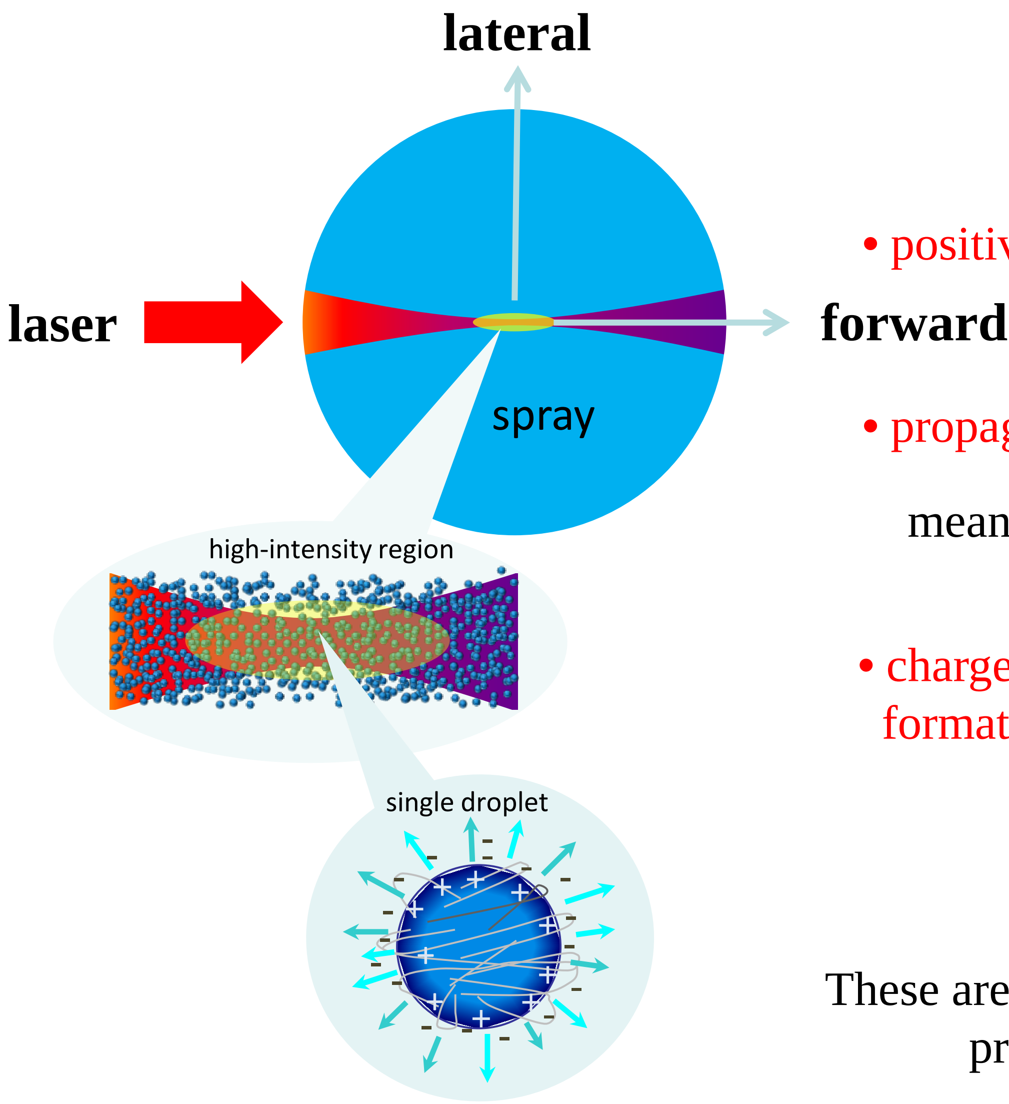
ethanol spray



water spray



negative ion formation in charge-exchange



- positive ions are accelerated from the droplets
- propagation of ion through the spray is collisional

mean free path length for oxygen L ~50 μm,
for protons : $L \gg d_{spray}$

- charge-exchange in a spray can explain the formation of negative ions:

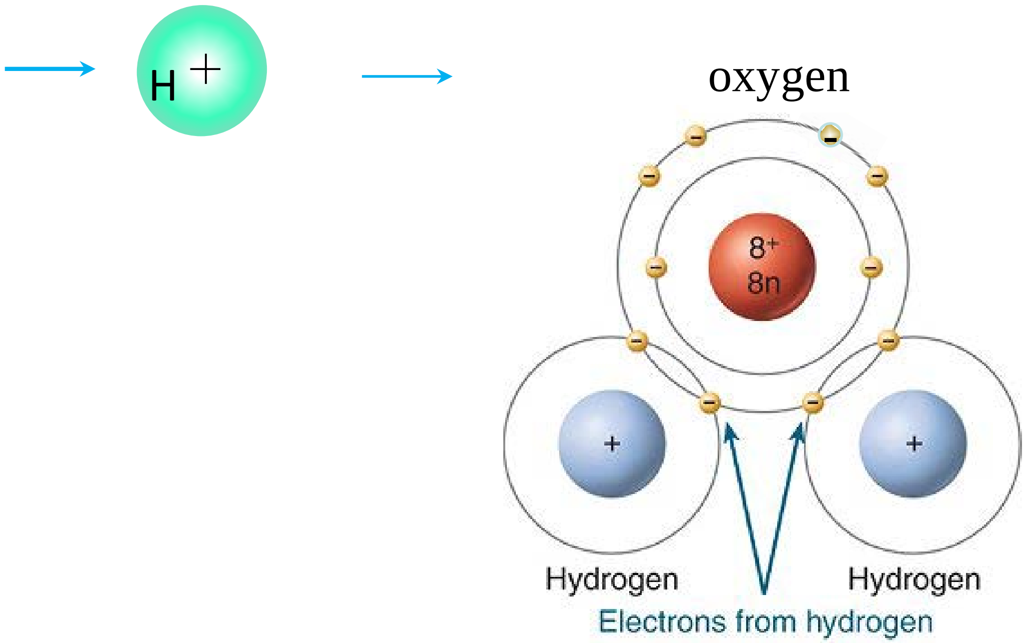
$$O^{n+} \leftrightarrow O^{(n-1)+}$$

electron capture and loss

These are resonant processes:
probability is max. if fast ion $v_{ion} \sim v_{bound\ el.}$
($1\text{MeV } O^{1+} = 3.4\times10^6$ m/s)

$(O \rightarrow O^-)$ $\sigma_{0\text{-}1} \sim 1\times10^{-16}$ cm^2 (for 0.1–1 MeV)

Artist's conception of electron capture by proton



$$A^+ \rightarrow A^0 \begin{cases} \nearrow A^- \\ \searrow A^+ \end{cases}$$

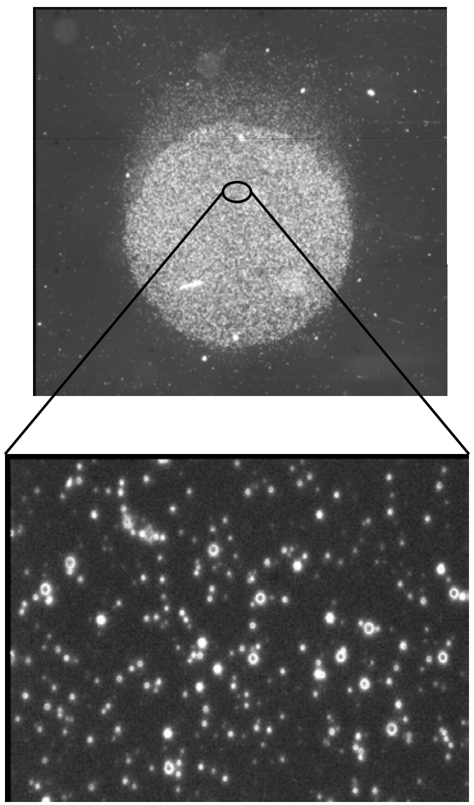
- the angular spread is very narrow, of the order of 1°

- the interaction proceeds almost elastically, without energy exchange

The ion that captures or loses an electron propagates essentially in the same direction and with the same energy as before the collision.

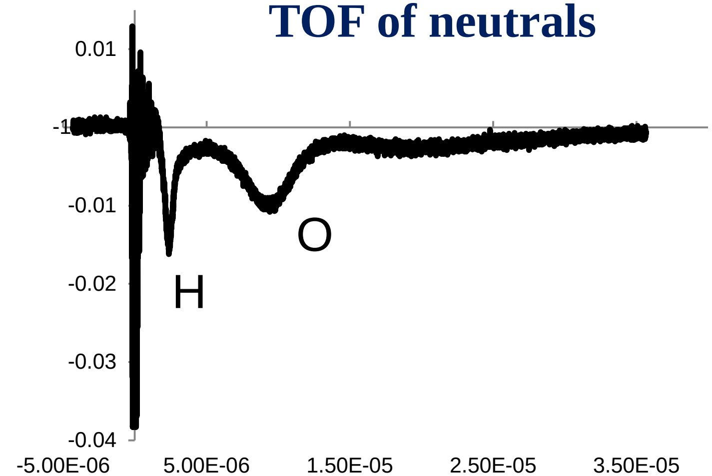
model implies the existence of fast neutrals with high energies

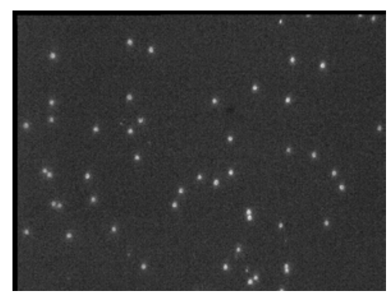
CR39 picture at “zero” point (1mm pinhole)



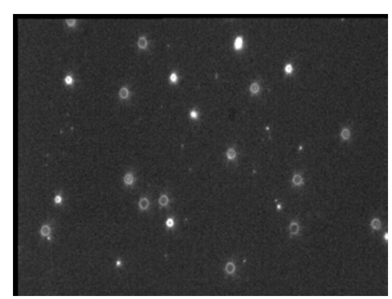
hydrogen and oxygen pits on zero point

TOF of neutrals





hydrogen pits



oxygen pits

Why the negative ions are interesting?

- Applications: tandem accelerators, ion beam microscopy and lithography, …

- Basic physics:

- in screening of nucleus the inter–electronic interactions become relatively more important than the electron–nuclear interactions.

The interplay of these attractive and repulsive interactions allows better understanding of atomic physics.

- electron correlation plays an important role.

- open problems:

- what is the role of droplet in the processes of negative ion creation
- H^- needs additional detailed investigations on:

  - spatial distribution
  - energy dependence on propagation length

- create other negative heavy ion species

  - to use other liquids

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